Human speckle perception threshold for still images from a laser projection system

Stijn Roelandt,[1,*] Youri Meuret,[2] An Jacobs,[3] Koen Willaert,[3] Peter Janssens,[4] Hugo Thienpont[1] and Guy Verschaffelt[5]

[1]*Brussels Photonics Team B-PHOT, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium;*
[2]*KU Leuven - Light & Lighting Laboratory, Gebroeders De Smetstraat 1, B-9000 Gent, Belgium*
[3]*iMinds SMIT, Vrije Universiteit Brussel, Pleinlaan 9, B-1050 Brussels, Belgium;*
[4]*Barco - Projection Division, Noordlaan 5, B-8520 Kuurne, Belgium;*
[5]*Applied Physics Research Group APHY, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium.*

** stijn.roelandt@b-phot.org*

http://www.b-phot.org/

Abstract: We study the perception of speckle by human observers in a laser projector based on a 40 persons survey. The speckle contrast is first objectively measured making use of a well-defined speckle measurement method. We statistically analyse the results of the user quality scores, revealing that the speckle perception is not only influenced by the speckle contrast settings of the projector, but it is also strongly influenced by the type of image shown. Based on the survey, we derive a speckle contrast threshold for which speckle can be seen, and separately we investigate a speckle disturbance limit that is tolerated by the majority of test persons.

OCIS codes: (030.6140) Speckle; (110.6150) Speckle imaging; (330.5020) Perception psychology.

References and links

1. K. Chellappan, E. Erden, and H. Urey, "Laser-based displays: a review," Appl. Opt. **49,** 79–98 (2010).
2. J. Hecht, "A short history of laser development," Appl. Opt. **49,** 99–122 (2010).
3. U. Weichmann, A. Bellancourt, U. Mackens, and H. Moench, "Solid-state lasers for projection," JSID **18,** 813–820 (2010).
4. J. W. Goodman, *Speckle phenomena in optics: theory and applications* (Roberts and Company, Englewood, 2007).
5. J. C. Dainty, "An introduction to 'Gaussian' speckle," Proc. Soc. Photo-Opt. Instrum. Eng. **243,** 2–8 (1980).
6. J. I. Trisnadi, "Speckle contrast reduction in laser projection displays," Proc. SPIE **4657**, 131–137 (2002).
7. M. S. Brennesholtz and E. H. Stupp, *Projection Displays* (Wiley & Sons, 2008).
8. L. Wang, T. Tschudi, T. Halldórsson, and P. R. Pétursson, "Speckle reduction in laser projection systems by diffractive optical elements," Appl. Opt. **37,** 1770–1775 (1998).
9. Y. M. Lee, D. U. Lee, J. M. Park, S. Y. Park, and S. G. Lee, "A study on the relationships between human perception and the physical phenomenon of speckle," SID Symposium Digest **39,** 1347–1350 (2008).
10. S. Roelandt, Y. Meuret, G. Craggs, G. Verschaffelt, P. Janssens, and H. Thienpont, "Standardized speckle measurement method matched to human speckle perception in laser projection systems," Opt. Express **20,** 8770–8783 (2012).

11. P. Janssens, P. Gerets, D. Maes, N. Vanden Bulcke, G. Van den Bergh, B. Van den Bossche, and K. Vermeirsch, “Fiber-Coupled Laser Cinema Projector,” in *Proceedings International Display Workshop 2011* (Nagoy, Japan, 2011), pp. 1885–1888.
12. ITU, ITURBT, “709-5 Parameter values for the HDTV standards for production and international programme exchange,” (2002).
13. H. Snellen, *Probebuchstaben zur Bestimmung der Sehschrfe* (Utrecht, 1862).
14. A. R. Reibman, S. Kanumuri, V. Vaishampayan, and P. C. Cosman, “Visibility of individual packet losses in MPEG-2 video,” in *Proceedings of IEEE Conference on Image Processing,* (Institute of Electrical and Electronics Engineers, Singapore, 2004), pp. 171–174.
15. B. A. Wandell, *Foundations of vision* (Sinauer Associates, 1995).
16. G. Wyszecki and W. S. Stiles, *Concepts and Methods, Quantitative Data and Formulae* (Wiley Series in Pure and Applied Optics, New York, 1982).
17. B. Pfaff. *GNU PSPP* (Version 0.8.3) [Software]. Available from http://www.gnu.org/software/pspp/get.html.
18. D. C. Montgomery, *Design and analysis of experiments* (Wiley & Sons, 2008).
19. P. A. Pappas and V. DePuy, “An overview of non-parametric tests in SAS: when, why, and how,” Paper TU04, Duke Clinical Research Institute, Durham, 1–5 (2004).
20. W. H. Kruskal and W. A. Wallis, “Use of ranks in one-criterion variance analysis,” Journal of the American statistical Association **47**, 583–621 (1952).

1. Introduction

Laser light sources are currently becoming very attractive in projection displays because of their wide color gamut, small étendue, long lifetime and high luminance [1–3]. Inherently connected to the use of lasers is the appearance of speckle. A speckle pattern is created by interference of (at least partially) coherent radiation that is scattered from a surface that is rough on the scale of the optical wavelength [4]. Speckle is observed as a granular pattern on the projection screen.

Speckle is visible on the projected images as a result of the projection screen’s roughness. Since this screen is optically rough and there are a large number of independent scattering elements that create this speckle pattern, the speckle pattern obeys to Gaussian statistics [5]. The amount of speckle is most commonly described by its speckle contrast value, $C = \sigma_I / \langle I \rangle$, where the numerator is the standard deviation of the intensity fluctuations and the denominator is the mean intensity. In the case of Gaussian speckle patterns, the speckle contrast value lies between 0 and 1.

Speckle masks the depicted information in projected images and, more importantly for projection applications, it is displeasing for a human observer. Therefore, it is imperative for any laser-based projector that the amount of speckle is reduced to an acceptable level.

Many different techniques currently exist in order to reduce speckle, most of them relying on the superposition of (at least partly) uncorrelated speckle patterns. These independent speckle patterns are instantaneously or time-sequentially overlapped on the screen. They are usually generated using wavelength decorrelation, spatial decorrelation, angular decorrelation, screen motion, polarization scrambling or any combination thereof [4, 6]. In each case, when N independent speckle patterns are overlapped, the speckle contrast will be reduced with a factor $\sqrt{N}$. The speckle contrast can thus be reduced to an arbitrarily small number, but reducing it comes at the expense of a more complicated, and therefore more expensive, projector design. It is thus crucial to know the maximal value of the speckle contrast that is allowed before speckle becomes disturbing for a human observer as this allows for a projector design that is both cost-efficient and of high-quality.

It is generally acknowledged that a human observer will no longer perceive speckle in projected images once the speckle contrast becomes sufficiently small. For example, in [7], it is reported that a speckle contrast of 2% is visible and may be disturbing. In [8], a speckle perception threshold of 4% was stated based on the fact that a human observer will not recognize intensity variations smaller than this limit. However, it can be argued that the perception of speckle is not the same as the human perception of intensity variations. Actual tests of the human speckle perception threshold were discussed in [9], resulting in a lower limit of the required speckle contrast of about 3%. This study was performed using only two participants, and the speckle measurement procedure was not clearly outlined.

Each of these previous studies have tried to identify the speckle perception threshold, which is not necessarily the same as the speckle contrast level that is perceived as being disturbing. An additional difficulty when comparing the reported values of the speckle perception threshold is that the measured speckle contrast strongly depends on the measurement procedure. The speckle contrast is usually quantified by capturing images with a CCD camera. In that case, the measured speckle contrast will depend on e.g. the camera's pixel size, focal length and f-number [10]. Thus, in order to compare speckle contrast values from different studies and/or from different projectors, it is important to fully disclose the speckle measurement procedure.

In the study presented here, we will investigate and compare the speckle perception threshold and the speckle level that is recognized as being disturbing by a large group of participants to a field test in a lab environment. We use a prototype laser projection system in these tests with variable speckle contrast and with which full-color stationary images can be projected. The amount of speckle is quantified for each projector setting by using the standardized speckle measurement procedure outlined in [10].

2. Projector setup

The projection setup consists of two projectors, one of which is the prototype laser projector [11], the other is a lamp projector. The setup of the projectors and the position of the five observers is depicted in Fig. 1. The laser projector has a resolution of 2048×1080 pixels. The lamp projector is a Barco RLM-W6 with an ultra-high-performance (UHP) lamp and a resolution of 1920×1080 pixels. The primaries of the laser projector are located at 640 nm for red, 532 nm for green and 465 nm for blue. The projection screen is a *matte white* DaLite screen with unity gain and a viewing angle of 120°. Its dimensions are 3×2.4 m^2. The speckle reduction factor can be changed by angular, spatial and/or wavelength decorrelation. Angular decorrelation was changed by modifying the f-number of the projector via a variable aperture inside the optical system. Wavelength decorrelation was obtained by using emitters with slightly different wavelengths. As such, the speckle contrast can be changed in a controllable way. We want to remark that we deliberately disabled some lasers during the subjective tests because the speckle contrast would otherwise be too low to evaluate the speckle threshold. The luminance of the projected images is set to 30 cd/m^2 and the room was darkened. The distance from the projector to the screen is 3 m and the distance from the screen to the viewer is on average 2.5 m, depending on the chair position. The white points of both projectors were experimentally verified to be equal to the CIE 1931 color space white point and the primaries of both projectors were matched according to the REC709-standard [12]. Since the color representation of both projectors is equal, the appearance of color in the images cannot influence the perception of speckle.

The total image areas on the screen of the laser and lamp projector largely overlap. Only the overlapping region of the screen was used in the test. During the tests, either the left hand side or the right hand side of each projector's image area is set to black. By only using half of the image plane for each projector, we can choose for each image in the sequence at which side of the screen we project the laser based image. This way, the observers have no a-priori knowledge of the position of the laser projector's image on the screen, which allows us to investigate differences in speckle and quality perception of the two projectors.

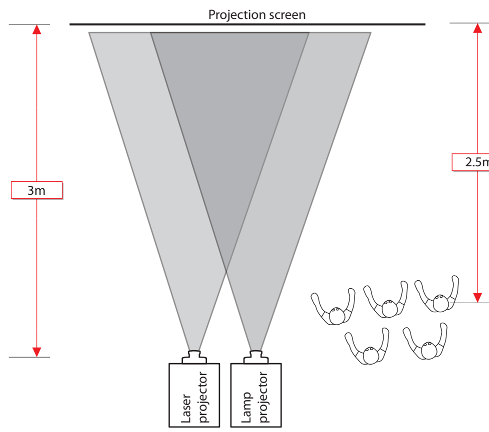

Fig. 1. Schematic of the setup. The projector is positioned at a distance of 3 m from the screen. The viewers are located at 2.5 m.

3. Image content and procedure of the subjective tests

In total, 8 groups each consisting of 5 people have participated to the tests. For each group, a separate session has been organized. The participants have been recruited from university staff and students. Each of the participants has filled in a printed questionnaire. The visual acuity of the participants is tested based on a Snellen chart [13]. The participants are also asked whether they suffer from color blindness.

3.1. Procedure for the evaluation of speckle using images with content

Before the actual tests, the speckle phenomenon is illustrated to the participants by projecting three test pictures using the laser projector set at a high speckle contrast value. After this learning step, 20 pairs of images are shown in a mirror configuration, i.e. the image and its horizontally mirrored version are shown on the left and right hand side of the screen. One of these images is generated by the laser projector, whereas the other one is generated by the lamp projector. We change the position of the laser/lamp images in a quasi-random way. Five different settings are used to vary the laser projector's speckle contrast value, which we quasi-randomly change from image to image during these tests. In order to investigate the influence of the image content on the speckle perception, we use six different images in the test sequence. The types of images are chosen in three main categories, namely images with a low amount of contrast (denoted as LC), images with a high amount of contrast (denoted as HC) and colorful images (denoted as CL). Again, the order at which the images are shown is varied in a quasi-random fashion. Each mirror-image pair in the test sequence is shown for 5 seconds, after which the participants are asked to give a score on the visibility of speckle in the right and left hand side image ranging from 1 (imperceptible) to 5 (very annoying). When the evaluation of the speckle is done, the next image pair in the sequence is displayed.

Table 1. Table showing the grading of the scores for speckle perception in the questionnaire.

Mark for the images how you see speckle	
Imperceptible	1
Perceptible, but not annoying	2
Slightly annoying	3
Annoying	4
Very annoying	5

3.2. Procedure for the evaluation of speckle using non-content images

After the evaluation of the image pairs, we start the second part of the survey in which we investigate the minimum speckle contrast value that can be detected by a human observer. During this stage, we project horizontal bars of the three primary projector colors and a white color bar as illustrated in Fig. 2. The participants are asked to write down whether or not they perceive

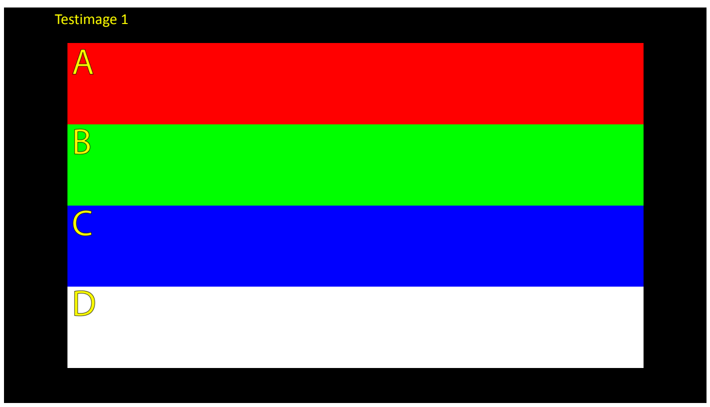

Fig. 2. Images shown when querying for the speckle detection limit, consisting of red, green, blue and white bars, created by the lasers' primaries.

speckle in each of the color bars individually. The procedure is repeated for a continuously decreasing setting of the laser projector's speckle contrast in six steps until the smallest speckle contrast setting is reached. To obtain the smallest speckle contrast, the light from the laser projector is mixed with light from the lamp projector. This way, lower speckle contrast values could be reached and we can quickly change between different speckle settings. This mixing of light is only used for the non-content images (horizontal bars). The luminance of the images, projected with both lamp and laser projector, was adjusted such that the luminance of the final image is always equal to 30 $\mathrm{cd/\,m^2}$. Please note that the perception of speckle can be dependent on the luminance of the projected images and will be a subject for future investigations. After that, the procedure is continued by stepwise increasing again the speckle contrast of the laser projector using the same step.

4. Speckle measurement setup

In the following section, the measurement setup used to objectively quantify the amount of speckle is presented, based on the findings presented in [10]. The measurement setup consists of a monochrome CCD camera with a pixel area of 4.40×4.40 µm^2. The camera lens has a fixed focal length of 16 mm and a fixed f-number $f/4$.

In order to objectively measure the speckle contrast and define a human speckle perception threshold, one should make sure the speckle contrast measured is independent of the projection system and is related to the human observer perception. As a consequence, the camera setting should exhibit a clear aperture of 3.2 mm and a square root ratio between the pixel area A_p and speckle area A_c of $\sqrt{A_p/A_c} = 0.54$ [10]. With the measurement settings of the CCD camera and lens used in our setup, however, we obtain a clear aperture of 4 mm and $\sqrt{A_p/A_c} = 1.83$.

In general, it is not recommended to measure the speckle contrast with any given camera setting and calculate backwards in order to obtain an objective speckle contrast value [10]. However, in this situation, we can do so since we know exactly how the projection system is designed and optimized. As such, it is possible to compensate for the incorrect settings of the camera lens if the deviation from the ideal settings is not too large, i.e. if for example the pixel averaging is not too large such that there is no information lost in the captured images.

Two speckle reduction mechanisms have to be compensated for due to the incorrect setting of the measurement parameters. The first one is the fact that the ratio of pixel to speckle area is not matched. The ratio $\sqrt{A_p/A_c}$ is larger than it should be, resulting in a lower speckle contrast. A correction will thus have to be applied that increases the speckle contrast with a factor $f_{\text{pixel averaging}}$. The second mechanism we have to correct for is due to the fact that the clear aperture of the camera is set at 4 mm, whereas it should in fact be 3.2 mm. The clear aperture of the camera is thus larger, resulting in less angular decorrelation and thus increasing the speckle value as compared to the standardized measurement procedure. As a consequence, the measured speckle contrast should be multiplied with a factor $f_{\text{ang decorr}}$. This assumption on angular decorrelation can be made since we know that the projection system completely overfills the aperture of the projection lens. To summarize, two correction factors should be calculated to correct for the non-ideal measurement settings, namely

$$f_{\text{pixel averaging}} > 1 \qquad \text{pixel averaging} \tag{1}$$

$$f_{\text{ang decorr}} < 1 \qquad \text{angular decorrelation} \tag{2}$$

The pixel averaging influence can be adjusted based on the simulation graph exhibited in Fig. 3 [10]. In this graph, we plot how the simulated speckle contrast depends on the ratio of the pixel area and the speckle area. In this simulation, the speckle contrast is calculated starting from a fully developed speckle pattern (for which $C = 1$). This pattern is then spatially divided into pixels, and the resulting digitized pattern is used to calculate the speckle contrast. For a human observer, the ratio $\sqrt{A_p/A_c}$ is 0.54, and the corresponding speckle contrast following from Fig. 3 is 0.99. Similarly, the parameters of our setup correspond to $\sqrt{A_p/A_c}$ being 1.83 which leads to a speckle contrast of 0.81. Therefore, the speckle contrast that was measured should be multiplied with a compensation factor of 1.22. The mismatch in clear aperture that influences the angular decorrelation can be adjusted for using the ratio of the solid angles. The speckle contrast in the case of angular decorrelation is proportional to the ratio of the solid angle subtended by the camera lens towards the screen over the solid angle subtended by the projection lens towards the screen, i.e. $\Omega_{camera}/\Omega_{projector}$. In our measurement settings, the clear aperture of the camera lens was larger and the speckle contrast will be too high. The

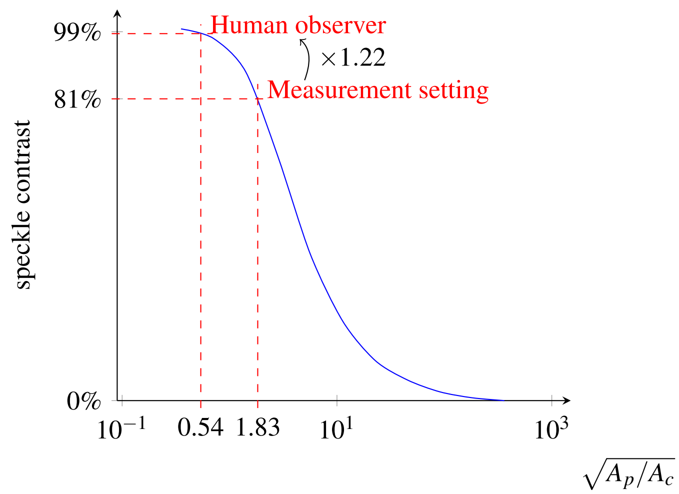

Fig. 3. Simulated effect of spatial averaging on the speckle contrast as a function of the square root of the ratio between the pixel area and the speckle size ($\sqrt{A_p/A_c}$). Backwards calculation from the measurement setting to the human observer situation results in a speckle contrast increase factor of 1.22.

correction factor can then be defined as

$$f_{\text{ang decorr}} = \sqrt{\frac{\Omega_{\text{correct settings}}}{\Omega_{\text{meas settings}}}} \qquad \text{where } \Omega = \sqrt{\frac{\pi\,(D/2)^2}{d^2}} \tag{3}$$

$$= \sqrt{\frac{\pi\,(3.2/2)^2}{(2.5\cdot 10^3)^2}} \cdot \sqrt{\frac{(2.5\cdot 10^3)^2}{\pi\,(4/2)^2}} \tag{4}$$

$$= 0.8 \tag{5}$$

where Ω is the solid angle, D is the clear aperture and d is the distance to the screen. Combining both correction factors, we find the total correction factor equal to

$$f = f_{\text{pixel averaging}} \cdot f_{\text{ang decorr}} = 1.22 \cdot 0.8 = 0.98. \tag{6}$$

The measured speckle contrast values are adjusted and now the values correspond with how a human observer evaluates speckle. As previously mentioned in Section 3, five different speckle settings have been used in the subjective tests when images with content are shown. The measured speckle contrast values for each of these settings are given for red, green and blue in Table 2. The speckle contrast values are different for the different primary colors due to specifics of the laser projector. For each of the settings, speckle is largest for the green primary. As we will explain in the next sections, we will specify the laser projector's setting based on the speckle contrast of the primary with the largest amount of speckle, which in the case of this projector is the green primary.

5. Images without content: speckle detection limit

We start our discussion of the subjective tests by looking at the responses to the second part of the questionnaire, which is related to the evaluation of the color bars, shown in Fig. 2. In

Table 2. Speckle contrast measured at each of the laser projector's speckle settings and for each of the primary colors.

Setting	C red [%]	C green [%]	C blue [%]	**C max [%]**
1	3.6	4.1	3.8	**4.1**
2	3.8	4.4	3.9	**4.4**
3	3.9	4.6	3.9	**4.6**
4	4.4	5.5	4.4	**5.5**
5	5.2	6.4	4.8	**6.4**

Fig. 4 we plot the percentage of participants that observe speckle for every primary color independently and for a white color bar as a function of the laser projector's speckle contrast. The speckle contrast is measured using the procedure outlined in Section 4. The results in Fig. 4 are represented as a scatter plot. The percentages of people noticing speckle when decreasing or increasing the speckle contrast of the projector was almost the same, so both data points are plotted. For each of the colors, we see that the percentage of participants that observe speckle is gradually increasing when the speckle contrast is increased. Additionally, a trend line is plotted through the data points such that a trend for all three primary colors is visible (see dashed line).

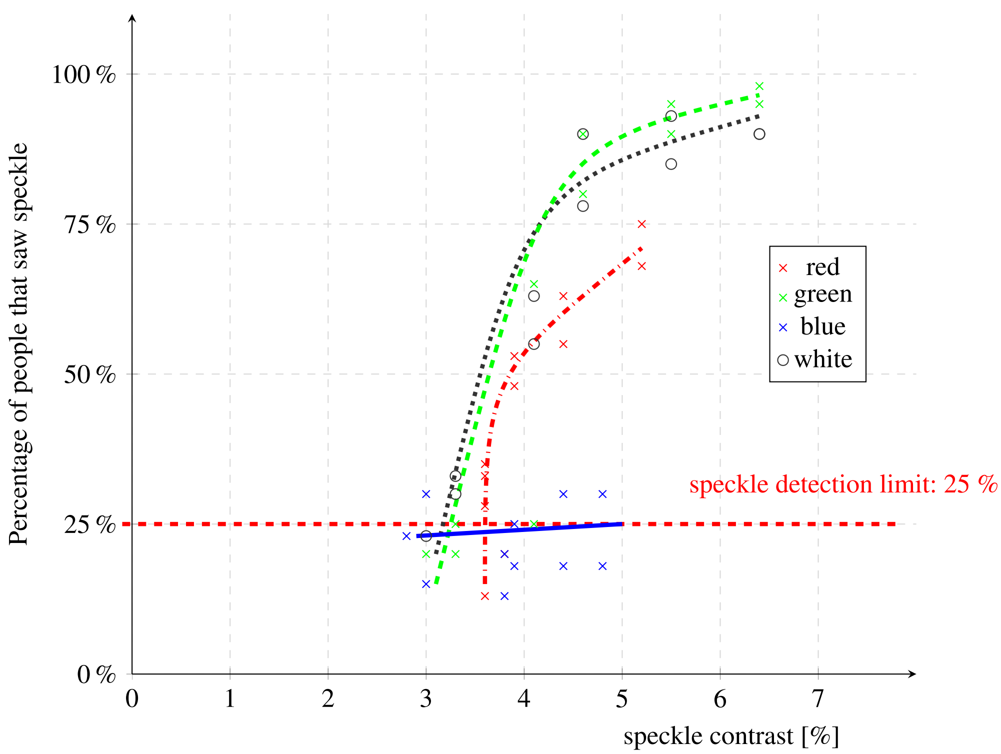

Fig. 4. Percentage of people that observe speckle for each of the projector's primary colors and for white as a function of the laser projector's speckle contrast. The dashed lines are trend lines of the data sets to show the trend of the different primary colors.

From Fig. 4 it is clear that the speckle perception is drastically different for different persons. If we look for example at the results for the green primary color, about 5 % of the participants do not observe speckle at the largest speckle setting (C = 6.4 %) but 20 % of the participants still observe it at the lowest speckle setting (C = 3.0 %). Therefore, it is not possible to define an absolute speckle detection limit. We will rather define it at a level for which a specific percentage of participants does not perceive speckle. We use in this study the level at which less than 25 % of the participants observe speckle as the speckle detection limit [14].

The speckle detection limit can be defined as the point where the trend line (dashed line) crosses the 25 %-level. This yields a speckle detection limit of C = 3.2 % for the green, C = 3.6 % for the red and C = 4.4 % for the blue primary color. Note that there is quite some fluctuation in the data set of the blue color, making it difficult to observe a clear trend for this color. This indicates that the viewers had a hard time noticing speckle at 465 nm for this projector and thus the threshold value for blue defined here is most probably a lower limit. Blue speckle is also harder to see because the blue photoreceptors (S-cones) in the human eye are much more sparsely distributed than the longer wavelength photoreceptors (M- and L-cones) [15], making the eye's effective pixel area for blue larger, and hence causing more speckle averaging. A more in-depth investigation is needed to define a precise threshold value for blue.

For the white color bar in this test, we observe in Fig. 4 that it closely follows the trend of the green primary color. This indicates that a mixing of primary colors does not lead to speckle reduction, but rather that the primary color with the largest amount of speckle determines the speckle perception of mixed colors. We attribute this effect to the fact that different primary colors are detected by different types of receptors (or a combination of them) in the human eye [16]. Furthermore, when the primary colors are mixed to produce a white image area, the speckle spots of each of the primary colors do not exactly overlap. The speckle spots have a different color compared to the background color perceived by the observers, and thus are easily noticed. As a consequence, the speckle contrast values for the white color are plotted using the speckle contrast values of the worst color, i.e. green. If one wants to quantify the amount of speckle in a laser projector with a single number, it is more appropriate to use the maximum speckle contrast C of each of the primary colors than to use an average of these speckle contrast values.

6. Images with content: speckle disturbance limit

In this section we analyze the speckle perceived by the participants when images with content are shown. The responses of the participants are statistically analyzed using the PSPP package [17]. The scores (or responses) are then used to calculate the so-called *mean opinion score* or MOS. This is the arithmetic mean of all the individual scores, and will range from 1 to 5. The first 5 (out of a total of 20) image pairs are considered to be part of a transition sequence during which the participants are getting used to the test procedure. In order for the results not to be influenced by any shift in the participants behavior due to their adaptation to the test procedure [18], the responses during the transition sequence are disregarded in the analysis.

Using the responses corresponding to the other 15 image pairs, we investigate if the amount of speckle is dependent on the different setup parameters for both the laser and the lamp projector. The parameters taken into account are the speckle contrast C of the laser projector, the image type, the visual acuity and the color blindness of the participants. The speckle scores given by the participants are not normally distributed, as can be seen in Fig. 5, where the histogram of the speckle MOS score is plotted for all user responses. The blue curve is a normal distribution fit based on the MOS score and the MOS standard deviation. Therefore, we have to make use of a non-parametric statistical test in order to analyse the data [19]. We investigate the user's quality assessment based on a non-parametric Kruskal-Wallis test [20]. The results of

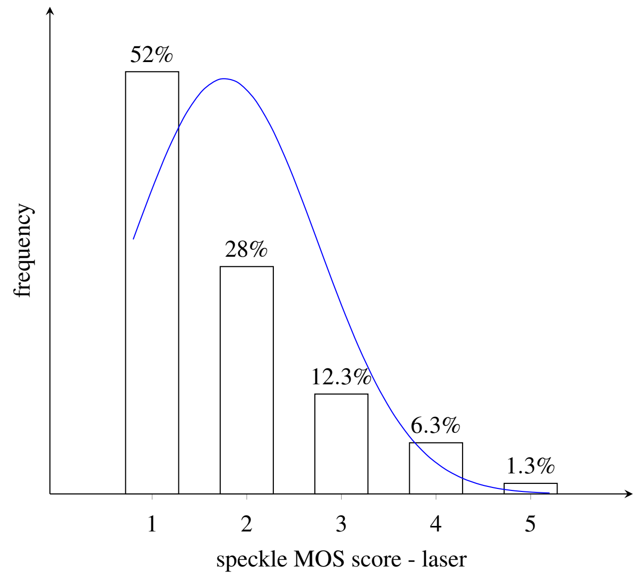

Fig. 5. A histogram of the speckle MOS score is plotted for all user responses. The blue curve is a normal distribution fit based on the mean MOS score and the MOS standard deviation.

this analysis are summarized in Table 3. In this table, we give the mean observer score (MOS) for speckle perception for both types of projectors. We also indicate in this table which parameters yield a statistically significant difference (at $p = 0.05$) in the speckle MOS. This implies that the chance of measured differences being the result of 'noise' (i.e. the null hypothesis) is less than 5 %. As can be seen in this table, the speckle MOS of the laser projector is only 1.77, which indicates that most users do not perceive speckle (MOS score 1) or perceive it without the speckle being disturbing (MOS score 2). Also in the lamp projector, with a speckle MOS of 1.37, speckle is apparently perceived by some of the observers.

Table 3. Average MOS values for speckle perception of the laser- and lamp-based projectors for all speckle settings and image types. Y (N) indicates that there is (is not) a statistically significant difference of the answers depending on the value of the parameter specified in each column, respectively.

	Speckle perception	
	Lamp	Laser
MOS	1.37	1.77
Speckle contrast laser	N	Y
Image type	Y	Y
Visual acuity	Y	N
Color blindness	N	Y

The most important result from Table 3 is that the speckle MOS for the laser projector depends on the projector's speckle contrast setting, on the type of image shown and on color blindness. The speckle MOS for the laser projector does not depend on the visual acuity of the participants, but we want to remark that the amount of participants that exhibited some loss in visual acuity was very limited. Also in the lamp projector, speckle is apparently perceived by some of the observers while the speckle contrast of the lamp projector is expected to be close to zero. The speckle MOS for the lamp projector depends on the image type, and also slightly on the visual acuity. In the next subsections we will investigate these dependencies in more detail.

6.1. Influence of the projector's speckle contrast

In this section we investigate how the user quality assessment depends on the setting of the laser projector's speckle contrast value. The user responses are organized into five data sets, each set corresponding to a particular setting of the speckle contrast as is shown in Table 2. We again use a Kruskal-Wallis test in order to identify statistically significant differences between the responses of the people for the different speckle contrast values. The results of this analysis are summarized in Table 4, in which we show the number of responses N and the speckle MOS of the laser projector for each setting of the speckle contrast. We also show the mean difference in speckle score between the different data sets and the statistical significance of these differences. The mean difference has to be interpreted as the mean value of the difference between the speckle score for the C value specified in the first column and the speckle score for the C value specified in the second row.

The largest speckle contrast setting (C = 6.4 %) clearly corresponds to the largest speckle score, and the differences with the other speckle contrast settings are statistically significant (see last column of Table 4). When decreasing the speckle contrast C to 5.5 % and 4.6 %, the speckle perception score decreases significantly. For still lower settings of C, the speckle MOS increases again slightly, but this increase is (at least for C = 4.1 %) not significant. These observations suggest that lowering the speckle contrast of the projector below C = 4.6 % does not result in a further improvement (i.e. a significantly lower speckle MOS) of the user's speckle perception. At C = 4.6 %, the speckle MOS is a mere 1.44, indicating that most observers do not perceive speckle or that they find it not disturbing for the six sample images used in the test.

Table 4. Analysis of speckle MOS and mean difference in speckle score of the laser projector's speckle perception and how it depends on the speckle contrast C. N is the total number of observations within each data set.

			Mean difference speckle score				
Speckle constrast	N	Speckle MOS	$C = 4.1$ %	$C = 4.4$ %	$C = 4.6$ %	$C = 5.5$ %	$C = 6.4$ %
$C = 4.1$ %	120	1.55	-	-0.17	0.11	-0.23*	-0.82**
$C = 4.4$ %	120	1.72		-	0.27**	-0.06	-0.65**
$C = 4.6$ %	120	1.44			-	-0.33**	-0.92**
$C = 5.5$ %	120	1.77				-	-0.59**
$C = 6.4$ %	120	2.37					-

* indicates differences that are statistically significant at $p = 0.05$.
** indicates differences that are statistically significant at $p = 0.01$.

Another way to assess the speckle perception in the laser projector is by directly comparing the speckle scores of the lamp and laser projector. During the test sequence, we always show two (identical but mirrored) images simultaneously of which one is projected by the lamp projector while the other is generated by the laser projector. This allows us to perform a pairwise comparison between the two projector types. As before, we use a non-parametric test because of the non-normal distribution of the users' responses. The results of a paired signed test are shown in Table 5, in which we give for each setting of C the speckle MOS values for both types of projectors. In this table, we also indicate whether or not the differences between lamp

Table 5. Comparison between lamp and laser projector based on speckle for different settings of the laser projector's speckle contrast C. Y indicates differences that are statistically significant.

Speckle contrast	Speckle MOS		
	Lamp	Laser	Significance
$C = 4.1$ %	1.35	1.55	Y
$C = 4.4$ %	1.35	1.70	Y
$C = 4.6$ %	1.38	1.44	
$C = 5.5$ %	1.46	1.77	Y
$C = 6.4$ %	1.32	2.37	Y

and laser projector are statistically significant. For each setting of C, the speckle MOS of the lamp projector is lower than that of the laser projector. This difference is significant for most settings, but not for C = 4.6 %. Another conclusion that can be drawn is that, when testing the performance of any laser projector, one should not aim at achieving a speckle MOS of 1. Rather, the quality of speckle perception will be statistically identical (at $p = 0.05$) to that of a lamp projector if the speckle MOS stays below a value of 1.5 on the speckle scale defined in Table 1.

6.2. Influence of the image type

The results presented in Table 3 indicate that the speckle perception of the laser projector depends on the type of image shown. In order to perform a further analysis of this effect, we have redistributed the user responses into data sets corresponding to the type of image shown. In Table 6, we show the results of a Kruskal-Wallis analysis used to identify statistically significant differences, together with the speckle MOS for each image type and the mean differences in speckle score between the different images.

Table 6. Analysis of speckle MOS and mean difference in speckle score of the laser projector's speckle perception and how it depends on the type of image shown. N is the total number of observations within each data set.

			Mean difference speckle score					
Image type	N	Speckle MOS	HC1	HC2	LC1	LC2	CL1	CL2
HC1	100	1.63	-	-0.62^{**}	-0.15	-0.34^{**}	0.4^{**}	-0.16
HC2	100	2.25		-	0.47^{**}	0.28	1.02^{**}	0.46^{**}
LC1	120	1.78			-	-0.19	0.55^{**}	-0.01
LC2	80	1.98				-	0.74^{**}	0.19
CL1	100	1.23					-	-0.56^{**}
CL2	100	1.79						-

* indicates differences that are statistically significant at $p = 0.05$.

** indicates differences that are statistically significant at $p = 0.01$.

The lowest speckle MOS is obtained for image CL1. This image contains a lot of high spatial frequency components in each primary color. The presence of such high frequency components in the image content clearly masks the perception of speckle. The image labeled HC2 results in the worst speckle score: the speckle scores for this image are significantly larger than for almost all other images. The image HC2 is characterized by large areas of uniformly-colored grey regions. From evaluations by the users, we attribute the high speckle score for uniform, white regions to the perception of colored speckle spots on top of the white background (see Section 5).

6.3. *Influence of the color blindness*

Another dependence of the laser projector's speckle score that turned up in Table 3 is the influence of color blindness of some of the participants. This effect is further detailed in Table 7, where we show the statistical analysis of the laser projector's speckle score. From this table, we can see that color blind participants perceived significantly less speckle than other participants: the speckle MOS of the color blind people is 0.36 lower than for the other participants. We attribute this effect to the integration of colors in the eye receptors leading to additional speckle reduction for color blind persons. However, as there are only three color blind persons in our test group, further research on a larger group would be required to confirm this result.

Table 7. Analysis of speckle MOS and mean difference in speckle score of the laser projector's speckle perception and how it depends on color blindness of the observer. N is the total number of observations within each data set.

			Mean difference speckle score	
Color blindness	N	Speckle MOS	Yes	No
No	555	1.80	-	-0.35**
Yes	45	1.44		-

* indicates differences that are statistically significant at $p = 0.05$.
** indicates differences that are statistically significant at $p = 0.01$.

6.4. *Worst case settings*

As we discussed in Section 6.2, the results listed in Table 6 clearly indicate that the speckle score of the laser projector is strongly influenced by the type of image shown. Therefore, we here want to complement the analysis of the laser projector's contrast setting by only looking at the user evaluations corresponding to image type HC2, as these images lead to the largest speckle score. The results of this analysis are given in Table 8, in which we again show the number of responses N, the speckle MOS of the laser projector and the mean differences in speckle score now only considering the image HC2.

Starting from the largest contrast setting, we can see in Table 8 that the speckle MOS of the laser projector is gradually decreasing when decreasing the projector's contrast setting. However, the analysis shows that only the differences with the setting C = 6.4 % results in statistically significant differences. For all settings of C, the speckle MOS is larger than 1.5, which indicates that the speckle in the laser projector is always perceived to be higher than for the lamp projector when considering the HC2 images.

7. Speckle disturbance limit

Based on the analysis presented in the previous section, it is clear that it is not obvious to define an absolute value of the speckle disturbance limit, as the speckle perception is strongly

Table 8. Analysis of speckle MOS and mean difference in speckle score of the laser projector's speckle perception for image HC2. N is the total number of observations within each data set.

			Mean difference speckle score				
Speckle constrast	N	Speckle MOS	$C = 4.1$ %	$C = 4.4$ %	$C = 4.6$ %	$C = 5.5$ %	$C = 6.4$ %
$C = 4.1$ %	20	1.90	-	-0.25	-0.05	-0.3	-1.15^{**}
$C = 4.4$ %	20	2.15		-	0.2	-0.05	-0.9^{**}
$C = 4.6$ %	20	1.95			-	-0.25	-1.1^{**}
$C = 5.5$ %	20	2.2				-	-0.85^{**}
$C = 6.4$ %	20	3.05					-

* indicates differences that are statistically significant at $p = 0.05$.
** indicates differences that are statistically significant at $p = 0.01$.

different from person to person. One can set this limit for example by requiring that a specified percentage of observers should find the speckle imperceptible (MOS score 1 in Table 1) or not annoying (MOS score 2 in Table 1). The limit set forward is than depending on the quality level that one wants to achieve, i.e. a more tolerant level will result in the projector being perceived by users as being of less quality.

A more stringent way to set the disturbance limit, is by requiring that users do not perceive a difference in speckle amount as compared to a lamp projector. When we use this limit, and consider a projector that is used to project all types of images, the speckle disturbance limit can be set to a contrast value C = 4.6 % (see Section 6.1). However, from the discussion in Section 6.4, we know that this disturbance limit only holds if a large majority of the projected images are not similar to HC2, i.e. if they do not contain large, uniformly colored areas. This might be true for some specific niche applications, but is not valid for most general purpose projection systems.

In order to further investigate this limit, we plot in Fig. 6 the cumulative percentage of responses for each of the speckle scores from Table 1 for different laser projector speckle contrasts (C). When considering the graph for C = 4.6 %, this limit corresponds to 90 % of the observers evaluating the speckle as being imperceptible or not annoying. The curve for C = 4.1 % is close to that for C = 4.6 %, which is in agreement with the statistical analysis presented in Section 6.1. (We remark that the curve for C = 4.4 % is not plotted as it closely follows that for C = 4.1 %). The curves for C = 5.5 % and C = 6.4 % are clearly lower than the one for C = 4.6 %, indicating that speckle is more strongly perceived for these settings.

In Fig. 6 we also show the cumulative percentage when only the responses to image HC2 are shown. Even for the smallest setting of C (i.e. C = 4.1 %), speckle is much more strongly perceived than when all images are considered. The cumulative percentage at a speckle score of 2 is only 70 % if we only consider the HC2 images, meaning that 30 % of the respondents find the speckle slightly disturbing or worse. For a system that is used to project all kinds of images, it can be argued that the speckle should not be disturbing irrespective to the image content that is being shown. The range of speckle contrast settings tested in this study was insufficient to find a setting that is suitable to fulfill this condition. In that case, it is more reasonable to estimate the speckle disturbance limit to be close or equal to the speckle perception threshold discussed in Section 5. The images tested in that section consist of uniformly colored bars and are thus rather similar in spatial characteristics to the HC2 image. The speckle detection limit discussed in Section 5 was set at the contrast value for which 25 % of the participants observe

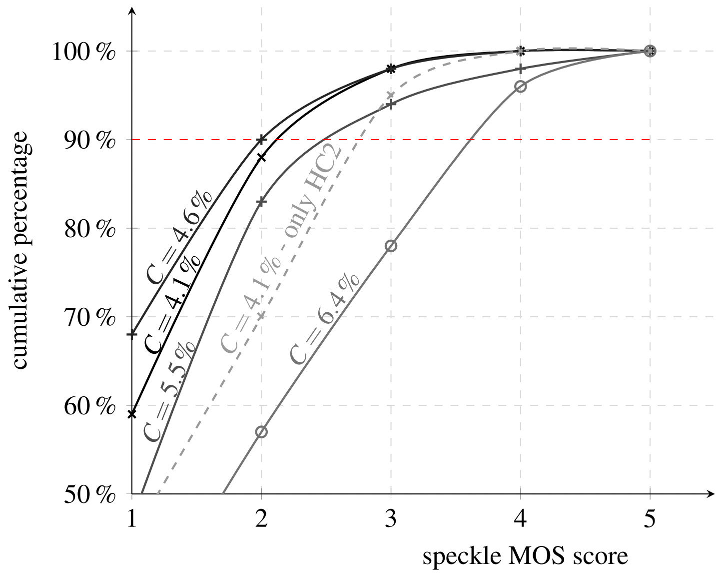

Fig. 6. Cumulative percentages versus the speckle score (scale defined by Table 1) for different laser projector speckle contrasts (C).

speckle. We argue here that persons who do not identify the presence of speckle in the uniform color bars of Section 5 will quantify the speckle amount in this section as “imperceptible”. As our setup on still images did not allow to go below 4.1 % of speckle, we must assume the disturbance threshold is somewhere between the detection threshold and our lowest speckle setting, yielding a contrast value between 3.2 % and 4.1 % for still images.

8. Conclusion

In this paper we studied the speckle detection and disturbance limit based on a study involving 40 participants. Both of these limits are user-dependent, and we use a statistical analysis of the responses in order to find significant parameters that influence the speckle perception.

The speckle detection limit has been determined by selecting the contrast level for which less than 25 % of the users observe speckle in uniformly colored image. This results in a detection limit of C = 3.6 % for the red (639 nm), C = 3.2 % for the green (532 nm) and C = 4.4 % for the blue (465 nm) primary colors. Another conclusion of this study is that the speckle detection when mixing primary colors, for example to obtain white regions, is similar to that of the primary color that contains the largest amount of speckle. The speckle contrast C of a projector should thus be specified either for each primary color, or the largest value should be given.

Since the speckle detection limit is not necessarily the same as the level of speckle at which it becomes disturbing for a human observer, we have also tested the latter based on a survey of the image quality using different settings of the projector’s speckle contrast. The speckle contrast is first measured using the standardized procedure outlined in Ref. [10]. In this test, we have only used still images. We want to remark that the speckle perception in movies might be different and will be the subject of future work.

In the speckle perception tests, speckle was also perceived by (some of) the observers when evaluating images projected by the lamp projector. As a consequence, an important conclusion of our study is that it is not necessary to aim at a speckle MOS of 1 when testing a laser projector. Since the speckle MOS value of a lamp projector is equal to 1.37 (based on the scale defined by Table 1) speckle perception tests resulting in a MOS value lower than 1.5 are actually statistically identical to that of a lamp projector. Remark that this number is equally useful when a quality scale is used that is different from the one shown in Table 1. In such a case, the 1.5 MOS value can easily be rescaled using the proper linear transformation.

The speckle perception is notably influenced by the content of the images. Therefore, different disturbance limits can be considered when designing a projector, depending on the targeted application. When the projector is aimed at showing images which contain only a small amount of low spatial frequency components, the disturbance limit is at C = 4.6 %. This is significantly larger than the speckle detection limit. However, for general purpose applications, which will typically also display images with large, uniform white regions, the disturbance limit is estimated to be between 3.2 % and 4.1 %.

Acknowledgments

The authors would like to acknowledge financial support from the Agency for Innovation by Science and Technology in Flanders (IWT), the Fund for Scientific Research (FWO), the Industrial Research Funding (IOF), Methusalem VUB-GOA, IAP BELSPO VI-10 under grant IAP P7-35 "photonics@be", and the OZR of the Vrije Universiteit Brussel.